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Molecular Cloud Evolution

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Abstract. I describe the scenario of molecular cloud (MC) evolution that has emerged over the past decade or so. MCs can start out as cold atomic clouds formed by compressive motions in the warm neutral medium (WNM) of galaxies. Such motions can be driven by large-scale instabilities, or by local turbulence. The compressions induce a phase transition to the cold neutral medium (CNM) to form growing cold atomic clouds, which in their early stages may constitute thin CNM sheets. Several dynamical instabilities soon destabilize a cloud, rendering it turbulent. For solar neighborhood conditions, a cloud is coincidentally expected to become molecular, magnetically supercritical, and gravitationally dominated at roughly the same column density, $N \sim 1.5 \times 10^{21} \text{ cm}^{-2} \approx 10 M_{\odot} \text{ pc}^{-2}$. At this point, the cloud begins to contract gravitationally. However, before its global collapse is completed ($\sim 10^7$ yr later), the nonlinear density fluctuations within the cloud, which have shorter local free-fall times, collapse first and begin forming stars, a few Myr after the global contraction started. Large-scale fluctuations of lower mean densities collapse later, so the formation of massive star-forming regions is expected to occur late in the evolution of a large cloud complex, while scattered low-mass regions are expected to form earlier. Eventually, the local star formation episodes are terminated by stellar feedback, which disperses the local dense gas, although more work is necessary to clarify the details and characteristic scales of this process.

1. Introduction

The molecular gas in the Galaxy exists in giant complexes (*giant molecular clouds*, or GMCs) of masses $\sim 10^{5-6} M_{\odot}$, sizes of several tens of parsecs, and mean densities $n \sim 100 \text{ cm}^{-3}$ (see, e.g., the review by Blitz 1993), and contain a large amount of substructure (parsec-scale *clumps* of densities $n \sim 10^3 \text{ cm}^{-3}$, and sub-parsec-scale *cores* of densities $n > 10^4 \text{ cm}^{-3}$). Molecular clouds (MCs) contain roughly half the gaseous mass in the Galaxy, and are the sites of all present-day star formation (SF) in the Galaxy. Thus, the study of their origin and evolution is crucial for our understanding of SF, besides the importance, on its own right, of understanding this fundamental component of the ISM.

The seminal paper by Oort (1954) postulated the existence of a cycle (now known as the *Oort cycle*), in which the expanding HII regions around newly formed massive stars form shells of cold gas around them. The shells subsequently fragment and produce a population of cloudlets, which then grow by coagulation until they become gravitationally unstable, at which point they proceed to collapse and form a new generation of stars, starting the cycle all over again. In this model, which was later developed by Field & Saslaw (1965), clouds were assumed to grow exclusively by coagulation

of randomly-moving small cloudlets. The same cloud growth process was assumed in later models, such as that by Norman & Silk (1980), which differed from the Oort model mainly in that the driving agent was considered to be winds from low-mass, T-Tauri stars rather than the ionizing radiation from massive stars, and the model by McKee (1989) for the SF rate (SFR) regulated by the background photo-ionizing radiation. The coagulation process implied very long ($\gtrsim 10^8$ yr) cloud growth times (Scoville & Hersch 1979; Kwan 1979), which were however ruled out on the basis of observational evidence by Blitz & Shu (1980). These authors proposed instead that MCs form and grow by a Parker (1966) instability triggered by spiral-arm shocks, and have lifetimes $\sim 10^7$ yr.

Ever since the times of those early models, MCs have been an odd component of the ISM. Because they are known to be strongly self-gravitating (Larson 1981; Myers & Goodman 1988) and at significantly higher thermal pressures than the mean ISM pressure (e.g., Myers 1978), they did not fit in thermal-pressure balance models of the ISM, such as that by McKee & Ostriker (1977). Instead, they have traditionally been considered to be in approximate virial equilibrium (Larson 1981; Myers & Goodman 1988), supported against their self-gravity by either the magnetic field (the so-called “standard” model of magnetically regulated SF; see, e.g., the reviews by Shu et al. 1987; Mouschovias 1991), or by turbulence driven by stellar feedback (the so-called “turbulent” model of SF; see the reviews by Vázquez-Semadeni et al. 2000; Mac Low & Klessen 2004; McKee & Ostriker 2007; Ballesteros-Paredes et al. 2007). In both cases, the gravitational contraction was assumed to be halted by either of the two mechanisms, and the clouds were assumed to reach near virial equilibrium. In the last decade or so, however, the paradigm about the formation, evolution and structure of MCs has changed significantly, and in the remainder of this review I will discuss this emerging new view.

2. Birth and infancy

2.1. Observational and numerical evidence on the clouds’ origin

As mentioned above, GMCs and their substructures had traditionally been thought to be in virial equilibrium. However, recent observations of GMCs in the LMC (Kawamura et al. 2009) suggest that the clouds are undergoing an evolutionary process, in which both their mass and their SF activity increase in time, going in ~ 25 Myr from masses $M \sim 10^{4.5-5} M_\odot$ and virtually no massive-SF to $M \sim 10^{5.5-6} M_\odot$ and a population of clusters and HII regions. This is consistent with the conclusion by Engargiola et al. (2003) that the GMCs in M33 are being assembled rapidly from the atomic component, with a prompt onset of SF.

Similar conclusions had been reached previously from numerical studies. Numerical simulations of the ISM at the kpc scale with turbulence driven by stellar feedback (supernova explosions, expanding HII regions; Bania & Lyon 1980; Chiang & Bregman 1988; Rosen et al. 1993; Rosen & Bregman 1995; Vázquez-Semadeni et al. 1995; Passot et al. 1995; Korpi et al. 1999; Ballesteros-Paredes et al. 1999a; de Avillez 2000; de Avillez & Breitschwerdt 2004, 2005) showed that compressive motions driven by large-scale gravitational instabilities in the diffuse ISM or by the global turbulence are able to form clouds on short timescales, essentially given by the turbulent crossing time across the distance necessary to collect the material that eventually reaches the cloud. This is facilitated by

the presence of cooling, which renders the medium highly compressible, even when no thermal instability (cf. §2.2.1) is present (Vázquez-Semadeni et al. 1996). Within such a dynamic scenario, Ballesteros-Paredes et al. (1999b) remarked that the clouds should not be considered as isolated objects, because a significant mass flux is expected to exist accross their boundaries, since the clouds are being assembled from material from the outside.

2.2. The physical processes

2.2.1. Instabilities galore!

The scenario of cloud assembly by convergent motions in the diffuse ISM (either driven by turbulence or by large-scale instabilities) was formulated analytically by Hartmann et al. (2001), who pointed out that the column density of cold atomic hydrogen necessary for H_2 and CO molecules to form is (van Dishoeck & Black 1988; van Dishoeck & Blake 1998)

$$N_{\text{H}} \sim 1\text{--}2 \times 10^{21} \text{ cm}^{-2}, \quad (1)$$

corresponding to $A_V \sim 0.5\text{--}1$, is very similar to the value necessary for the same gas to become gravitationally unstable (see also Franco & Cox 1986), and to the column density necessary for the gas to become magnetically supercritical, at a typical interstellar magnetic field strength of $B \sim 5\mu\text{G}$. This implies that when an initially atomic cloud is assembled by a convergent velocity field in the diffuse ISM, it should become molecular, self-gravitating, and magnetically supercritical at roughly the same time. We now discuss this phenomenology in some more detail.

A fundamental physical ingredient aiding the formation of dense atomic and molecular clouds is thermal instability (Field 1965), which is a consequence of the various radiative heating and cooling processes operating on the atomic ISM (for a modern discussion, see Wolfire et al. 1995). The atomic ISM is subject to the so-called *isobaric* mode of this instability: for densities in the range $\sim 1\text{--}10 \text{ cm}^{-3}$ ($T \sim 5000\text{--}500 \text{ K}$), the gas *loses thermal pressure* upon a dynamic compression (for a pedagogical discussion, see the review by Vázquez-Semadeni 2009), implying that after the compression it will be underpressured with respect to its surroundings, and will continue to be squeezed by them until it exits the thermally unstable range, at which point any further compression again increases its thermal pressure, until it eventually reaches pressure equilibrium with its surroundings, but at a much higher density and lower temperature. This is the basis of the well-known two-phase model of the atomic ISM (Field et al. 1969), originating the warm-diffuse and cold-dense phases of this ISM component, which are respectively referred to as the *warm* and *cold neutral media* (in turn, respectively, WNM and CNM).

The above discussion assumes that the gas is in the thermally unstable range to begin with. However, Hennebelle & Péroult (1999) showed that transonic compressions (i.e., of Mach number $\mathcal{M}_s \gtrsim 1$) in the *stable* warm phase can nonlinearly trigger a transition to the cold phase, so that cold clouds can be formed out of the stable WNM in the presence of transonic turbulence, which is indeed observed in this medium (Kulkarni & Heiles 1987; Heiles & Troland 2003). Alternatively, large-scale ($\gtrsim 1 \text{ kpc}$) instabilities in the diffuse medium, such as gravitational (e.g., Elmegreen 1994), Parker (Parker 1966) or magneto-Jeans (Kim et al. 2002), can provide the driving forces for these motions.

The gas cooled and compressed by this process to form a cloud is subject to a large number of dynamical instabilities. It has been long known that compressed layers formed by the collision of gas streams are nonlinearly unstable, meaning that the layers become turbulent when the colliding flows have sufficiently large velocities (Hunter et al. 1986; Stevens et al. 1992; Vishniac 1994). This process is known as the *nonlinear thin-shell instability* (NTSI). Furthermore, the presence of cooling lowers the required inflow velocities to destabilize the layers (Pittard et al. 2005). Finally, the Kelvin-Helmholtz and Rayleigh-Taylor instabilities are also expected to operate during the formation of a cloud. The interplay of all these instabilities has been investigated numerically by Heitsch et al. (2005, 2006). In summary, *convergent motions in the WNM are expected to produce turbulent CNM clouds.*

2.2.2. Evolution of the mass-to-magnetic flux ratio

Another crucial ingredient in MC dynamics is the magnetic field, and in particular, the mass-to-magnetic flux ratio (M2FR). As it is well known, the magnetic field can support a cloud against the latter’s self-gravity if the M2FR, or, equivalently, the ratio of column density to field strength, exceeds some critical value which, for a cylindrical configuration, is given by (Nakano & Nakamura 1978)

$$\Sigma/B \approx (4\pi^2 G)^{-1/2}, \quad (2)$$

where Σ is the mass column density. We denote by μ the value of the M2FR normalized to the critical value. Thus, a *magnetically subcritical* cloud has $\mu < 1$, and can be supported by the magnetic field, while a *supercritical* one has $\mu > 1$, and cannot be magnetically supported (e.g., Shu et al. 1987; Mouschovias 1991). In the “standard” model of SF, most clouds were assumed to be strongly magnetically subcritical, and thus globally supported by the field. SF was thought to occur on long timescales and involving small fractions of the clouds’ mass because, in the dense cores, the process known as *ambipolar diffusion* (AD) allows a redistribution of the magnetic flux, so that they can continue to contract quasi-statically, until their M2FR finally becomes supercritical, and then the cores collapse.

It is a very common practice to assume that the M2FR is a conserved quantity as long as the flow behaves ideally (i.e., AD is negligible). After all, for an isolated cloud of fixed mass, the mass is constant by construction, and the magnetic flux is conserved by the flux-freezing condition (see, e.g. Shu 1992). However, the M2FR refers to the mass within flux tubes, and in general, field lines do not end at the “edge” of a cloud, but rather continue out to arbitrarily long distances. In fact, it is well possible that magnetic field lines circle around the whole Galaxy. Now, eq. (2) implies that a flux tube is supercritical beyond an *accumulation length* given by (Mestel 1985; Hartmann et al. 2001)

$$L_{\text{acc}} \approx 470 \left(\frac{B}{5\mu\text{G}} \right) \left(\frac{n}{1\text{ cm}^{-3}} \right)^{-1} \text{ pc}, \quad (3)$$

so that, in principle, the entire ISM is supercritical, at least near the midplane. However, in the case of a forming CNM cloud, what is relevant is the M2FR *of the dense gas that makes up the cloud*, since the cloud is up to 100× denser than its surroundings, and thus it is the main source of the self-gravity that the field has to oppose. Thus, in this problem, natural boundaries for up to where to measure the M2FR are provided by the bounding surface of the dense gas.

Accumulation of material is *not* opposed by the magnetic field if it occurs along field lines, and so this can occur freely in the ISM. When compressions occur at an angle with the field, it has been shown by Hennebelle & Pérault (2000) that, up to a certain angle that depends on the Mach number of the inflows and the field strength, the inflow is reoriented along the field lines, and it behaves as if the compression were parallel to the lines. Beyond that angle, the compression behaves essentially as if it were perpendicular to the field, and the flow bounces off, not forming any cloud. Thus, in what follows, we consider the case of a cloud forming along field lines. Equation (2) can be rewritten as

$$N_{\text{cr}} = 1.45 \times 10^{21} \left(\frac{B}{5\mu\text{G}} \right) \text{ cm}^{-2}, \quad (4)$$

implying that the column density for a cloud to become supercritical is very similar to that for molecule formation to begin, and for the cloud to become gravitationally unstable (cf. eq. 1). Thus, we can infer that, *as a cloud forms and grows out of a compression in the WNM, it should become molecular, supercritical, and gravitationally unstable at roughly the same time.*

Figure 1 shows the evolution of the M2FR in two numerical simulations of cloud formation by Vázquez-Semadeni et al. (2011 in prep.; see also Banerjee et al. 2009), illustrating the growth of the M2FR. In these simulations, two cylindrical streams of radius 32 pc and length 112 pc each, are set to collide against each other at the center of a 256-pc numerical box along the x -direction, so that the cloud is a thin cylindrical layer perpendicular to the inflows. The M2FR is measured for each line of sight (LOS) perpendicular to the cloud, which is defined as the cylindrical volume of radius 32 pc and length 20 pc centered at the numerical box center. For each LOS, the M2FR is measured as the ratio Σ/B_{\parallel} , where B_{\parallel} is the field component parallel to the LOS and Σ is the mass column density along each LOS. Thus, these measurements constitute *upper limits* to the real M2FR (for a detailed discussion, see Vázquez-Semadeni et al. 2011). The simulations have mean magnetic field strengths of 3 and 4 μG , and $\mu = 0.91$ and 0.68, respectively. That is, both simulations are globally subcritical, implying that no subregion of it can be supercritical (Vázquez-Semadeni et al. 2005) as long as the flow remains ideal. Values of μ greater than those of the whole box indicate that the measured values overestimate the actual μ . Nevertheless, for a real cloud not limited by the box size, the magnetic criticality is expected to eventually become > 1 .

These conclusions are consistent with observational results showing that the CNM clouds are in general magnetically subcritical (Heiles & Troland 2005, sec. 7), while molecular structures appear to be critical or supercritical in general (Bourke et al. 2001; Troland & Crutcher 2008)

2.3. The early stages: thin CNM sheets

The early stages of cloud formation were investigated analytically and numerically by Vázquez-Semadeni et al. (2006), determining the structure and physical conditions (density, temperature, and expansion velocity of the phase transition front) in the incipient cloud as a function of the Mach number of the converging gas streams, before the dynamical instabilities have time to grow. Figure 2 shows the structure of the cloud (*left panel*) and the dependence of the physical properties of the cloud on the Mach number of the inflowing streams (*right panel*).

One important implication of the study by Vázquez-Semadeni et al. (2006) is that, in its initial stages, the forming cloud is expected to be a thin CNM sheet, since it

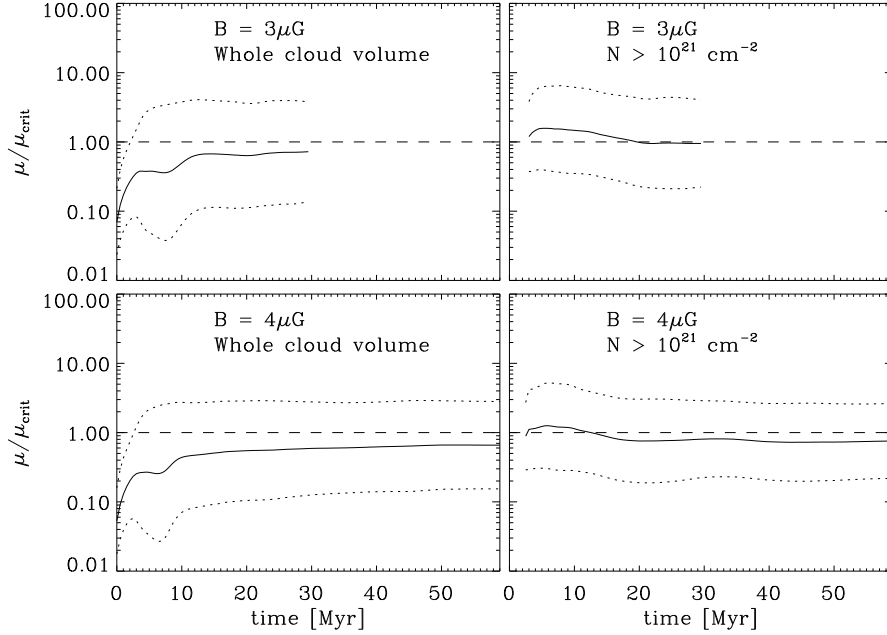


Figure 1. Evolution of the normalized M2FR, μ , for two numerical simulations by Vázquez-Semadeni et al. (2011, in prep.). See text for details on the simulations. The *top panels* refer to the simulation with $\langle B \rangle = 3\mu\text{G}$, while the *bottom panels* refer to the simulation with $\langle B \rangle = 4\mu\text{G}$. The *left panels* refer to measurements performed on the entire “cloud” volume, while the *right panels* refer to measurements performed only on those lines of sight for which the number column density satisfies $N > 10^{21} \text{ cm}^{-2}$. The *solid lines* denote the average of μ over all LOSs, while the *dotted lines* denote the 3σ deviations from the mean. The growth of μ from very small values to near unity during the first 10 Myr of evolution is clearly seen, especially in the plots for the whole cloud.

forms at the essentially two-dimensional interface between the colliding streams. After a few Myr of evolution, the predicted thin sheet has column densities that agree very well with the CNM sheets reported by Heiles & Troland (2003). Thus, it is suggested that such thin CNM sheets may constitute the earliest phases of MC evolution. Note, however, that a GMC may never form if the mass involved in the streaming flows is not high enough to attain the column densities necessary for molecule formation.

3. Maturity: Gravitational contraction and star formation (child bearing)

3.1. A distribution of collapse timescales

As discussed in §2.2.2, as a cloud grows, it should become molecular, supercritical, and gravitationally unstable at roughly the same time. This result implies that by the time a GMC forms, it should be contracting gravitationally, since it cannot be supported by the magnetic field because it is already supercritical, and it is not forming stars yet, so no additional turbulence that can support the cloud can be injected into it yet.

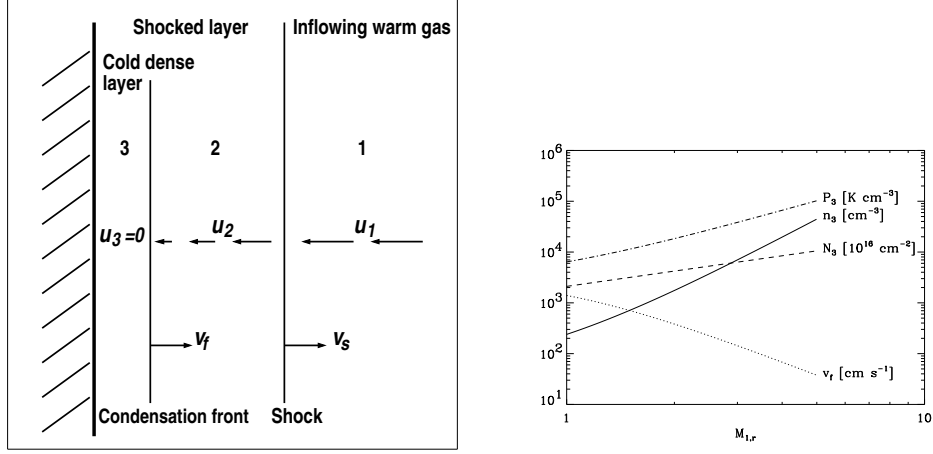


Figure 2. *Left panel:* Schematic illustration of the structure of a cloud formed by the collision of oppositely-directed WNM streams. The streams are assumed to collide along the horizontal axis. Only the right half of the system is shown, with the left stream replaced by a wall. The inflowing gas approaches from the right, and shocks at the interface between regions 1 and 2. The shock heating throws the post-shock gas out of thermal balance between heating and cooling, and so the gas cools as it flows towards the 2-3 interface. At the latter, the gas undergoes a phase transition (condenses) to the CNM, and settles into a dense, cold layer (region 3). The phase transition front moves outwards from the collision wall at speed v_f . *Right:* Pressure P , number density n , outwards speed of the phase transition front v_f , and column density N after 1 Myr of evolution, of the thin layer, all as a function of the Mach number of the inflow stream. From Vázquez-Semadeni et al. (2006).

However, the initial turbulence produced by the convergent gas streams has a crucial role in the subsequent development of the cloud and its SF activity. Numerical simulations by various groups (Koyama & Inutsuka 2002; Audit & Hennebelle 2005; Heitsch et al. 2005; Vázquez-Semadeni et al. 2006) have shown that the “clouds” are actually a mixture of warm and cold gas (see also Hennebelle & Inutsuka 2006). This is illustrated in Fig. 3 (*left panel*), which shows the granular, fractal density structure observed in a high-resolution (10000^2 zones) numerical simulation by Hennebelle & Audit (2007). The density field has a wide probability density distribution function PDF (Fig. 3, *right panel*), and thus, when gravity is included, this density PDF implies the existence of a wide distribution of free-fall times (Fig. 4; Heitsch & Hartmann 2008), with the bulk of the mass remaining at relatively low densities. This implies that a small fraction of the mass in the cloud will collapse, and thus SF will begin, *before* the global collapse of cloud as a whole is completed, on timescales ~ 10 Myr.

This kind of evolution, which we refer to as *hierarchical gravitational collapse* was first observed numerically in the simulations by Vázquez-Semadeni et al. (2007), and is very similar to the notion of hierarchical gravitational fragmentation introduced long ago by Hoyle (1953), except that in that proposal, the density fluctuations were assumed to be linear, and so they all had essentially the same free-fall time as the large-scale cloud, while here they are nonlinear, with shorter timescales than the cloud, due to the initial turbulence induced by the very process of assembly of the cloud.

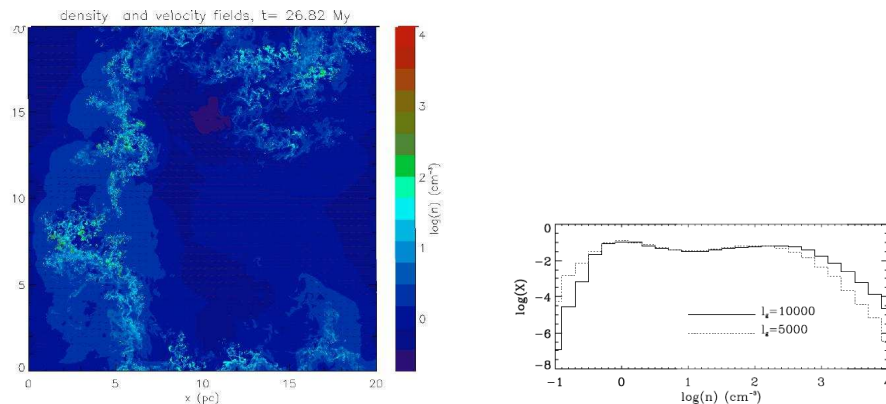


Figure 3. *Left:* Density and velocity fields in a two-dimensional numerical simulation of colliding flows in a 20-pc numerical box, with a resolution down to a scale of 2×10^{-3} pc. Note the extremely granular texture of the density field. *Right:* Volume-weighted probability density function (PDF) of the density field for this simulation (*solid line*) and for a similar one with lower (half) the resolution (*dotted line*). From Hennebelle & Audit (2007).

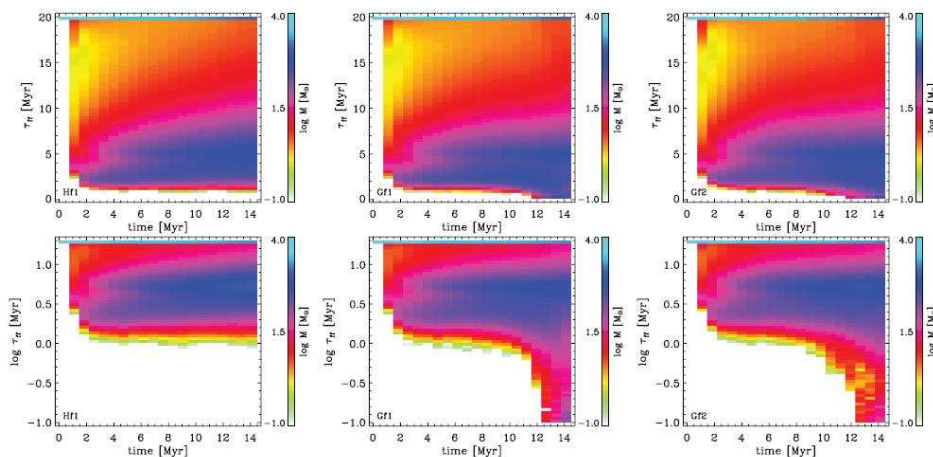


Figure 4. Mass at a given free-fall time as a function of time in three different numerical simulations of cloud formation by colliding streams by Heitsch & Hartmann (2008), with the free-fall time axis binned linearly in the *top* panels, and logarithmically in the *bottom* ones. It is seen that the bulk of the mass remains at low densities, with long free-fall times. From Heitsch & Hartmann (2008).

3.2. Low- and high-mass star-forming regions

The distribution of density fluctuations produced by the initial turbulence has another implication: a clump mass spectrum is produced. From high-resolution simulations, Hennebelle & Audit (2007) reported a power-law shape of the spectrum at high masses of the form $dN/dM \propto M^{-\beta}$, with $\beta \sim 1.7$, in good agreement with observational determinations of the mass spectrum for CO clumps (Motte et al. 1998; Kramer et al. 1998; Heithausen et al. 1998). It is well known that this form of the mass spectrum implies

that most of the mass is in the more massive clumps, even though they are less numerous.

Of course, the less massive structures are expected to be embedded in the larger-mass, lower-density ones in a hierarchical fashion (Vázquez-Semadeni 1994). This implies that the low-mass structures should be expected to terminate their collapse and form stars earlier than the more massive ones, and so a prediction from the present scenario is that a large molecular complex should contain a relatively large number of low-mass, somewhat older (by a few Myr) star-forming regions, and a smaller number of massive regions, formed later, yet containing most of the mass. The latter is consistent with the well known result that most stars are formed in massive, cluster-forming regions (Lada & Lada 2003). Of course, this picture neglects triggering of secondary SF by previous generations of stars, which complicates the picture.

This scenario has been quantified in a numerical simulation by Vázquez-Semadeni et al. (2009), who selected a typical example of the early-forming, low-mass regions, and the most massive cloud formed by collapse of the cloud complex at large from a numerical simulation of cloud formation by Vázquez-Semadeni et al. (2007). This simulation used a similar setup to that of the simulations by Banerjee et al. (2009), discussed in §2.2.2, but with no magnetic fields. Vázquez-Semadeni et al. (2009) showed that indeed the masses, sizes, velocity dispersions, and SFRs of the two regions were respectively consistent with observations of such types of regions. Moreover, they compared the distributions of masses, sizes and densities of the dense cores within the massive region, showing that they were very similar to the corresponding distributions for the set of cores in the Cygnus-X region by Motte et al. (2007). In summary, this analysis suggested that the formation of low- and high-mass star-forming regions by this mechanism is viable.

4. Old age: Stellar feedback (popping all over)

Once SF begins in a cloud, the newly formed stars feedback on it via either low-mass star outflows, which inject momentum, or ionizing radiation and supernova explosions from massive stars. The effect of this feedback on the parent cloud has been extensively studied by numerous groups. For a detailed discussion, see the review by Vázquez-Semadeni (2011, in preparation). Here we focus only on whether the feedback is able to bring the parent cloud to a quasi-static equilibrium or whether, instead, it ends up dispersing the cloud. This is an issue about which much effort is currently being devoted, and because of that, no conclusive answer is yet available.

In recent years, simulations of multiple jets in parsec-scale clumps (Nakamura & Li 2007; Carroll et al. 2009) have suggested that bipolar outflows are sufficient to drive and maintain the turbulence in parsec-scale clumps, and to maintain the latter in a near-hydrostatic equilibrium. However, in those works the clumps occupied the entire numerical box, and therefore the simulations lacked the contracting motions of the rest of the MC in which they are embedded.

A simplified model of the effect of massive-star feedback through HII-region expansion on the *global* evolution of GMCs was performed by Krumholz et al. (2006). These authors computed the time-dependent virial *balance* (not necessarily equilibrium) of a spherical GMC under the effect of its self-gravity and the energy injection of its embedded HII regions. In their simplified model, the SFR self-regulates, and causes oscillations of the clouds, which are finally dispersed after a few crossing times.

Full numerical simulations of HII-region feedback in the context of a fully-evolving and contracting GMC have been recently performed by Vázquez-Semadeni et al. (2010), who again used the setup described in §2.2.2, now in adaptive mesh refinement (AMR) simulations which allowed an effective resolution of ~ 0.03 pc, and that included feedback from a single-mass population of stars. These authors found that the feedback affects the immediate surroundings of the recently formed stars, thus reducing the SFR, but is not capable of reverting the global contraction of the GMC. Similar results have been obtained in high-resolution simulations at the clump-scale with outflow feedback by Wang et al. (2010). Those authors have found that the accretion that feeds the most massive star is not restricted to the core in which the star is being formed directly, but rather can be traced out to the scale of the whole clump containing the core, in spite of the fact that the outflows distort this flow, reducing the SFE of the system.

In summary, the available numerical evidence suggests that the scenario of gravitationally contracting MCs is maintained even in the presence of stellar feedback. The latter may be an important source of energy for driving the turbulence at the clump (parsec) scale, but has a harder time halting the gravitational contraction at the scale of the whole GMC (tens of parsecs). The calculations by Krumholz et al. (2006) and Vázquez-Semadeni et al. (2010) suggest that low-mass clouds are more readily destroyed by the feedback than more massive ones. Nevertheless, the numerical experiments performed so far are relatively scarce, and have used a limited set of initial conditions. A more complete coverage of parameter space, such as that conducted by Rosas-Guevara et al. (2010) for the variability of the SFR with the initial conditions, and with a more accurate modeling of the stellar feedback, is necessary to better understand the details of cloud dispersal.

5. Conclusions

5.1. Summary

The scenario of MC formation and evolution (under solar neighborhood conditions) discussed in the previous sections can be summarized as follows:

- The route to the formation of a GMC starts with a large-scale, moderately supersonic converging motion in the WNM, which may be driven either by large-scale instabilities, the passage of a spiral-arm or supernova shock, or by intermediate-scale generic turbulence in the WNM.
- The compression nonlinearly triggers a phase transition to the CNM, forming a large, though not very dense, cold atomic cloud. The earliest stages of these clouds may constitute the thin CNM clouds reported recently by Heiles & Troland (2003). At later times, a combination of the Kelvin-Helmholtz, Rayleigh-Taylor, nonlinear thin-shell and thermal instabilities destabilizes the cloud, rendering it turbulent and clumpy.
- If sufficient mass is available in the converging flow that a column density $\sim 1.5 \times 10^{21} \text{ cm}^{-2}$ is reached in the newly formed cloud, then the cloud begins to be dominated by self-gravity (rather than by the confining pressure [thermal+ram] of its surroundings) and also reaches a high enough extinction ($A_V \sim 1$) to allow the formation of CO molecules. Moreover, for a fiducial value of the mean

Galactic magnetic field of $5\mu\text{G}$, such a cloud should be near to becoming magnetically supercritical as well. So, for solar neighborhood conditions, a growing cloud should become molecular, self-gravitating and magnetically supercritical at approximately the same time.

- A cloud that has reached such a column density then begins to contract gravitationally. However, the clumps produced by the various instabilities, which have shorter free-fall times than the bulk of the cloud, culminate their collapses before the bulk of the cloud does. Star formation thus begins a few Myr after the cloud’s global contraction has started, but a few Myr before the bulk of the cloud cumulates its own collapse.
- The collapse of isolated, low-mass clumps produces scattered low-mass star-forming regions, while the collapse of the bulk of the cloud produces high-mass star-forming regions.
- The termination of a SF episode in a cloud is still not fully understood from the available numerical simulations. More complete coverage of parameter space and with more detailed modeling of the feedback is necessary. In any case, the attainment of a nearly hydrostatic equilibrium appears very difficult. Instead, it appears that a cloud may begin to be destroyed or dispersed locally, while the outer layers may still be falling in, establishing a complicated flow with both infall and outflow.

5.2. Implications: hierarchical gravitational contraction

The evolutionary scenario for MCs described here strongly suggests the ubiquitous existence of generalized gravitational contraction in MCs and their substructure, given the approximate simultaneity of the onset of gravitational contraction with the onset of molecule formation and the attainment of magnetic supercriticality. This implication is in fact consistent with a growing body of observational results. In particular, principal component analysis of the contributions to the velocity dispersion in MCs and their substructure invariably show a “dipolar” main component, indicating that the dominant contribution comes from a large-scale (i.e., at the scale of the full structure observed) velocity gradient (Heyer & Brunt 2007; Brunt et al. 2009) which is consistent with a global contraction or shear of the cloud, but inconsistent with solid-body rotation (M. Heyer, priv. comm., 2010). Also, studies comparing specific regions with numerical simulations (Hartmann & Burkert 2007; Peretto et al. 2007) have shown that those regions are well modeled by gravitationally contracting structures. Finally, recent studies of massive star-forming regions by (Galván-Madrid et al. 2009; Csengeri et al. 2010) have provided evidence of the existence of *hierarchical accretion flows* at multiple scales in the regions. The notion of hierarchical gravitational fragmentation has recently been formulated analytically by Field et al. (2008), who have proposed the existence of a gravitationally driven cascade from the large to the small scales in MCs, analogous to a turbulent cascade, except that the quantity being cascaded is mass rather than energy.

Moreover, recent observations by Heyer et al. (2009) having much higher angular and spectral resolution and higher dynamic range in column density than earlier studies (e.g., Solomon et al. 1987), suggest that MCs do not, after all, have a roughly constant column density Σ , but rather span up to two orders of magnitude in this variable, and

that the velocity dispersion actually scales with size *and* column density as

$$\sigma_v \propto (\Sigma L)^{1/2}. \quad (5)$$

Recently, Ballesteros-Paredes et al. (2010) have proposed that this scaling is exactly what is expected from a hierarchical gravitational cascade, in which, rather than virial *equilibrium*, the governing relation is simply energy conservation during the contraction, so that the gravitational and kinetic energies satisfy

$$|E_g| = E_k, \quad (6)$$

from which eq. (5) follows directly. It is noteworthy that, at face value, eq. (6) seems to fit the data better than the virial equilibrium condition $|E_g| = 2E_k$, as shown in Fig. 5, although large uncertainties, especially in the mass determinations, prevent any firm conclusions. Interestingly, note that free-fall implies *larger* velocities than virial equilibrium, contrary to the standard notion that velocities higher than virial imply lack of gravitational binding.

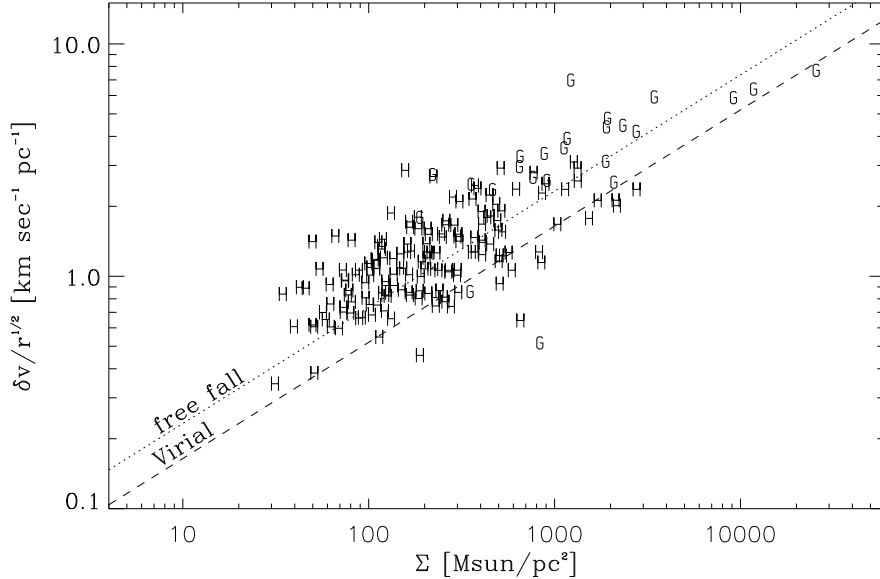


Figure 5. Massive dense cores from Gibson et al. (2009, labeled “G”), and clouds and clumps from Heyer et al. (2009, labeled “H”) in the $\sigma_v/R^{1/2}$ vs. Σ plane, where σ_v is the velocity dispersion, R is the region size, and Σ is the mass column density. The straight lines show the loci of virial equilibrium, $|E_g| = 2E_k$, and of energy conservation under free-fall, $|E_g| = E_k$. From Ballesteros-Paredes et al. (2010).

It is important to remark that the hypothesis that MCs might be undergoing generalized gravitational contraction is not new. It was first proposed by Goldreich & Kwan (1974). However, it was soon deemed untenable by Zuckerman & Palmer (1974) who argued that, if the clouds were in free-fall, then a simple estimate obtained by dividing the total molecular mass in the Galaxy by the mean free-fall time would imply a SFR roughly two orders of magnitude larger than observed. However, this conundrum

may not pose a serious problem if the star-forming activity of the clouds is terminated prematurely by the feedback from the first stars formed. More work to understand the details of this process is still needed.

5.3. Final remarks

The picture of MC evolution described in this review appears promising as a self-consistent scenario that connects the dynamics of the ISM at large with the physical properties of MCs and their star-forming properties. However, several features still need to be worked out in more detail, such as the precise form in which stellar feedback terminates a SF episode and disperses a cloud locally, and at what scales can this process be considered in an averaged sense, if at all. Also, more quantitative statistical issues, such as the fraction of the time, and of the stellar production of the clouds, is spent under the magnetically subcritical and supercritical regimes, respectively.

Finally, it is important to remark that the present scenario is likely to only apply directly to solar neighborhood-like conditions. In particular, it may need modification for regions like the molecular ring of the Galaxy, or to galaxies where the disk is mostly molecular, as in those cases the atomic component may be absent, at least locally. In those cases, it is possible that the entire molecular ring or disk is the equivalent of the isolated GMCs we have discussed here, and that the phase transition occurs at the boundaries of these regions, both radially and vertically. More work is needed in order to assess this.

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